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A Comparison of Structural Analysis Techniques for the Excalibur 155-mm Artillery Shell's Canard Actuation System

by James M. Bender and Lyonel E. Reinhardt

ARL-TR-3409 **March 2005**

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14. ABSTRACT

A structural finite element analysis of the four-axis canard actuation system (CAS) of the Excalibur 155-mm artillery projectile is presented. This is an improved version of an earlier two-axis design that will increase its maneuverability and accuracy. CAS receives control signals from the global positioning system guidance module of the Excalibur, thus enabling mid-course trajectory corrections. CAS is being analyzed to assess the structural robustness of the design to ensure that it can sustain the severe launch environment of high-performance 155-mm howitzers and can function as designed.

15. SUBJECT TERMS

artillery; canard actuation system; Excalibur; 155-mm artillery

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1. Introduction

The Excalibur projectile (see figure 1) is a 155-mm cargo carrier that can be launched from towed and self-propelled howitzers. This developmental projectile contains state-of-the-art guidance and control devices that are capable of providing mid-course trajectory corrections based on global positioning system satellite information. The canard actuation system (CAS) is a sub-unit of the projectile that is situated forward of the payload bay and aft of the guidance module that contains the inertial measuring unit (IMU) and guidance signal processing. At apogee, CAS deploys canards for steering control. The four-axis CAS differs from the previous version in that it is not roll controlled (course correction during rotation). All four canards can operate independently for maximum control. As in the previous two-axis model, the unit must sustain the severe gun-launch environment design load of 19,000 g's (which includes a 1.25 safety factor) while supporting the mass of the guidance unit, fuze, and expulsion charge above it.

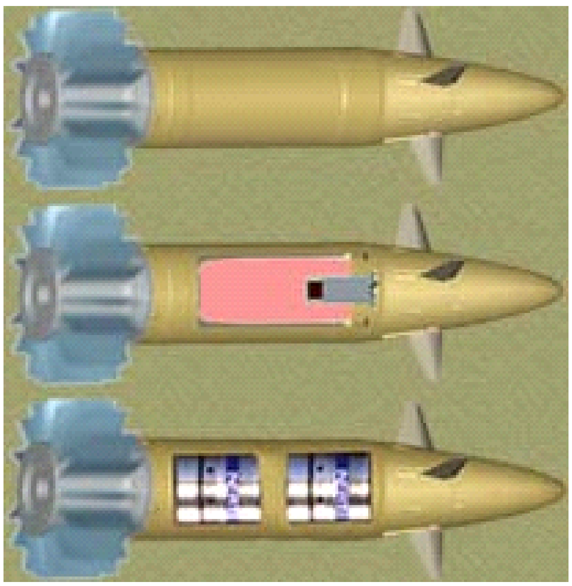

Figure 1. Excalibur 155-mm artillery projectile with payload variations.

2. Structural Analyses

Two independent structural analyses were performed. The first analysis was performed by the U.S. Army Research Laboratory (ARL) acting as an independent agency. ARL used the ANSYS[1] structural analysis code. The other analysis was performed by the sponsoring agency,

[1]ANSYS, which is not an acronym, is a registered trademark of ANSYS, Inc.

the Fire Support Armaments Center at Picatinny Arsenal, New Jersey. They performed an analysis using (ABAQUS)[2] and took advantage of the near half-symmetry of the structure and eliminated small features deemed structurally insignificant. ARL analyzed the full model. The comparison of the two analyses will give decision makers a certain level of confidence in the modeling techniques and will allow them to make a judicial decision that balances expediency and accuracy. It is envisioned that a simpler, defeatured model would allow faster turn-around of parametric analyses where the highly detailed model will boost confidence in the structural integrity of the final design.

2.1 Analysis by ARL

The ANSYS finite element analysis (FEA) program was employed to structurally analyze the four-axis CAS unit and compare results to a crush test of the unit in a laboratory testing environment. The crush test subjects the unit to compressive loading similar to that during gun-launch conditions with an added 5% safety factor (analysis with the required 25% safety factor will be performed at another time). Strain data from that test were compared to the strains predicted by the ANSYS model as a means of validating the finite element model. Drawings and electronic renderings (e-Drawings[3], initial graphics exchange specification [IGES] files) were received from Raytheon Missile Systems, Inc, the contractor for the CAS (figure 2). They were read into SolidWorks[4] virtual prototyping software, to prepare them for input into ANSYS. The assembly shown consists of a stack of two thick aluminum plates, which houses the control mechanisms. They are housed in an aluminum aeroshell with attachment clamp rings on the top and bottom. This section sits atop the payload compartment and below the ogive. The unit receives signals from the guidance section above (not shown) for in-flight navigation. The canards are stowed until the projectile achieves apogee, at which point, they are deployed by squibs (i.e., small explosive caps), lock in position, and commence control. The aeroshell and clamp rings hold the plates together in a compressive pre-load. The plates are bolted together as well.

The IGES files were imported into SolidWorks for refinement before being read into ANSYS. There, the solid model components were meshed into a structural finite element model as shown in figure 3. All mating interfaces were meshed with contact elements, thus allowing the two parts to meet, slide, or separate, depending on the state of stress between them. The two internal sections are shown in figure 4. The aluminum housing contains these parts and the stack is secured by a snug ring as shown, which pre-stresses them in compression. The two internal components are also held together by four bolts.

[2]ABAQUS, which is not an acronym, is a registered trademark of ABAQUS, Inc.

[3]e-Drawings is a registered trademark of Geometric Software Solutions Co., Ltd.

[4]SolidWorks is a registered trademark of Solid Works Corporation.

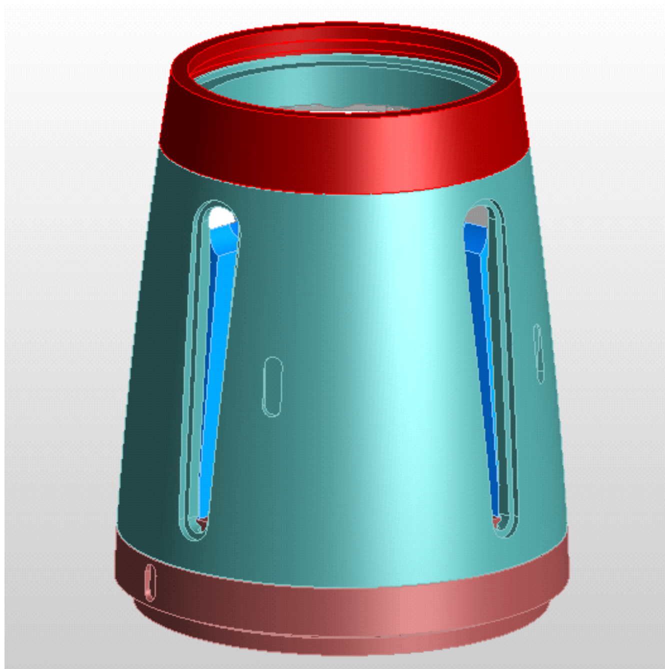

Figure 2. Solid model of the CAS module.

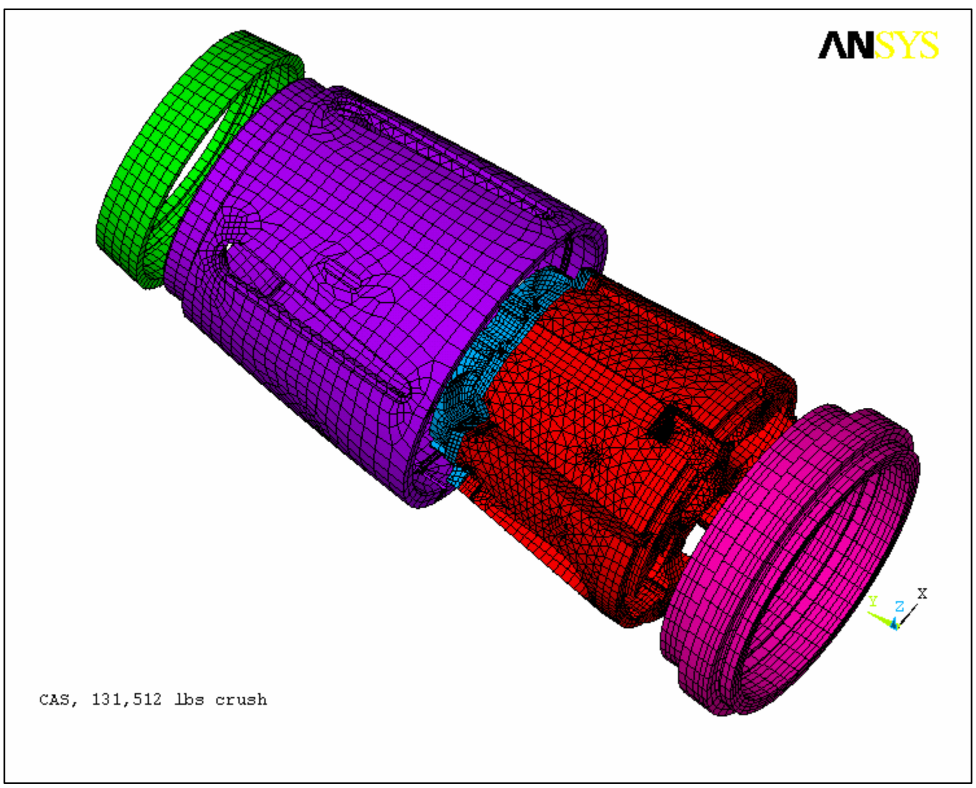

Figure 3. Finite element model of CAS (exploded view).

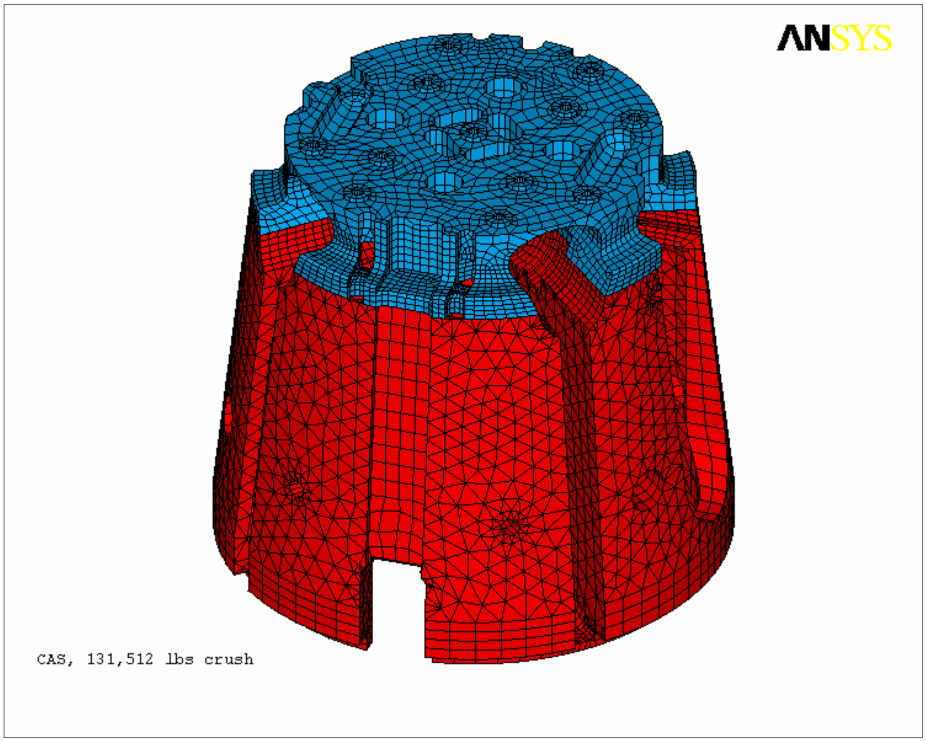

Figure 4. Internal components that comprise the stack.

The boundary conditions consistent with those from the physical test were applied to the finite element model of the CAS. Two tooling parts were modeled and affixed to the top and bottom of the assembly as shown in figure 5. These parts model the constraints that the actual projectile would impose on the CAS. Figure 6 shows the CAS prototype in the load machine ready for the test. Fifty-six strain gauges were affixed to the unit as well as a displacement transducer to measure overall axial deflection and a load transducer to track the applied load. These readings will be presented later for comparison to the FEA model.

2.2 Finite Element Analysis Results

The first result examined was the overall response of the structure to axial compression displacement. These data indicate whether the global stiffness of the test specimen agrees with the FEA model (see figure 7). Furthermore, it indicates whether all ten contact surfaces are behaving as specified according to the individual contact stiffnesses. Most of the strain data comparisons are discussed later, but the overall structural stiffness is assessed in figure 8 so that the global boundary conditions and response can be validated before we proceed to each measurement location. The global compression value modeled as –0.039 compares favorably with the measured response of –0.040 inch.

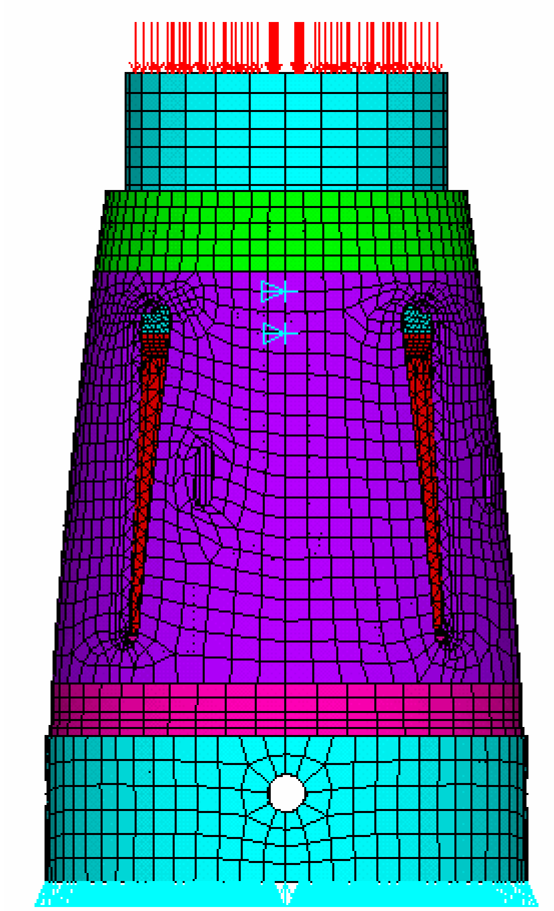

Figure 5. Finite element model with boundary conditions.

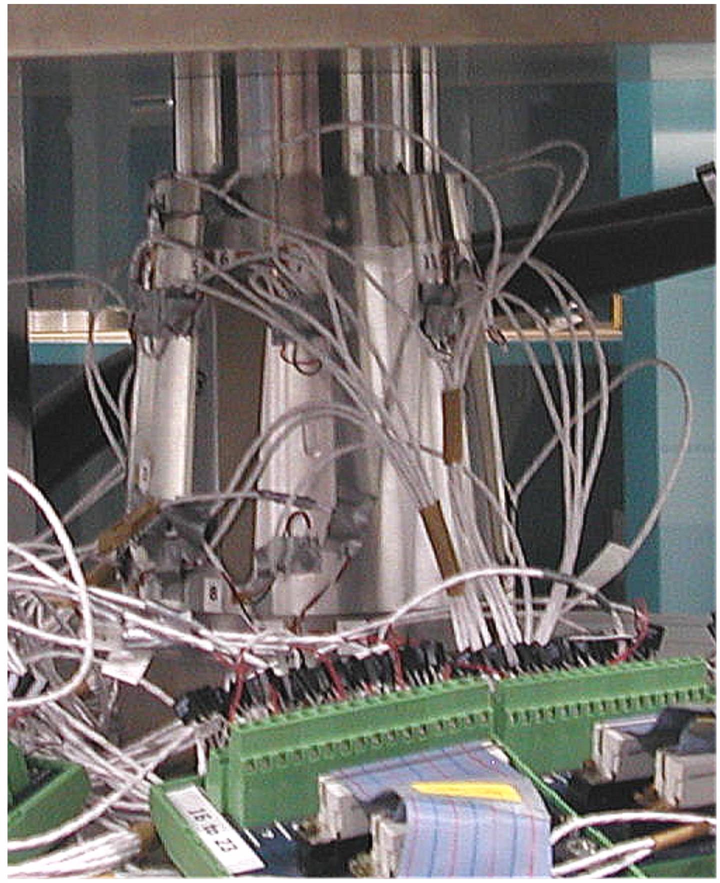

Figure 6. Prototype CAS ready for testing.

20% gauges: Numbers 7, 11, 21, 25, 29, 31
All others 5% gauges

Clocking of CAS defined by lug

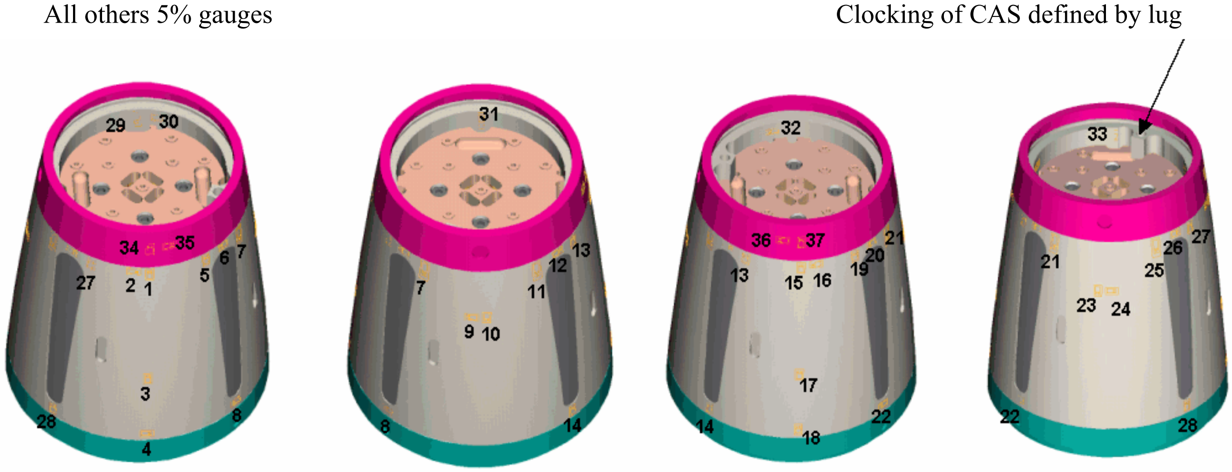

Figure 7. Prototype CAS location of strain gauges.

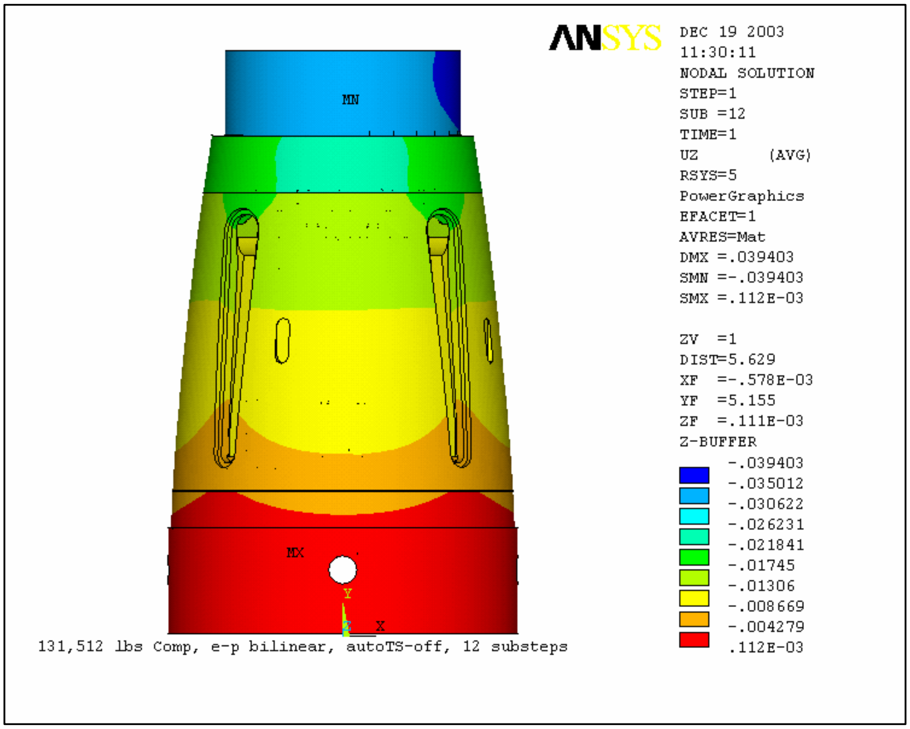

Figure 8. Overall compression measurement.

For the present test, we achieved the maximum load of 131,512 lb incrementally by increasing the load at a rate of 5,000 lb/sec. Strain gauge readings were taken every 1/8 second. All data were written to a database file. The readings at maximum load were extracted and are listed in table 1 where they are compared to the ANSYS predictions.

Possible sources of error between the strain gauge readings and the ANSYS prediction include

1. Grid coarseness: The strain patches will occupy an area with a varying number of finite element nodes underneath it. Ideally, a large number of nodes would yield an accurate modeling of the strain in the area, e.g., 6 to 8 nodes under a patch. However, central processing unit time and memory resources might be challenged with a large amount of nodes throughout the structure. A judicial selection of a quantity of nodes will give acceptable results without straining computer resources.

2. The drawings of the CAS specify an amount of pre-load on the internal stack to assure that they are tightly packed. The resulting tension on the outer casing would quantify this pre-load but was not measured. Although the strain would be small (<3% of expected total strain), it does contribute to the combined error.

Table 1. Comparison of ARL predictions to actual strain gauge readings, PMP + 5% (μ strains).

(Actual gauge reading/ANSYS estimate)				
gauge_1	**gauge_2**	**gauge_3**	**gauge_4**	**gauge_5**
-918/-879	673	-1470/-1719	553/528	-1930/-1757
4.2%	*	**-16.9%**	**4.5%**	**8.9%**
gauge_6	**gauge_7**	**gauge_8**	**gauge_9**	**gauge_10**
432/319	-1630/-1344	-192/-175	629/585	-1690/-2100
26.1%	**17.5%**	**-8.8%**	**6.9%**	**24.2%**
gauge_11	**gauge_12**	**gauge_13**	**gauge_14**	**gauge_15**
-2070/-1897	590/485	-1700/-1596	-197	686/785
8.3%	**17.8%**	**6.1%**	*	**-14.4%**
gauge_16	**gauge_17**	**gauge_18**	**gauge_19**	**gauge_20**
-1470/-1428	-1740/-1771	496/535	-2080/-1537	299/319
2.8%	**-1.8%**	**7.8%**	**26.1%**	**-6.7%**
gauge_21	**gauge_22**	**gauge_23**	**gauge_24**	**gauge_25**
-2160/-1319	-54	636/641	-1840/-1763	-1930/-1853
38.9%	*	**-0.8%**	**4.2%**	**4.0%**
gauge_26	**gauge_27**	**gauge_28**	**gauge_29**	**gauge_30**
509/316	-1780/-1806	-37	-1580/-1293	210
37.9%	**-1.5%**	*	**18.2%**	*
gauge_31	**gauge_32**	**gauge_33**	**gauge_34**	**gauge_35**
-2500/-1605	553/335	-2360/-2332	-1360	
35.8%	**39.4%**	**1.2%**	**Not modeled**	**Not modeled**
gauge_36	**gauge_37**	**gauge_38**	**gauge_39**	**gauge_40**
			60400*	
Not modeled	**Not modeled**	**Not modeled**	**Gauge failure**	**Not modeled**
gauge_41	**gauge_42**	**gauge_43**	**gauge_44**	**gauge_45**
21400*	-9830*	60400*	-1080/-906	-931/-435
Gauge failure	**Suspicious**	**Gauge failure**	**16.1%**	**53.3%**
gauge_46	**gauge_47**	**gauge_48**	**gauge_49**	**gauge_50**
		-60400*	118	-208
Not modeled	**Not modeled**	**Gauge failure**	*	*
gauge_51	**gauge_54**	**gauge_55**	**gauge_56**	**gauge_57**
-382/-485	588/589	1040/686		
26.9%	**0.2%**	**34.0%**	**Not modeled**	**Not modeled**
gauge_58	**gauge_59**	**load lbs**	**disp in**	
		-131,512	-0.0400/0.0394	
Not modeled	**Not modeled**		1.5%	

*Finite element grid too course in the area for accurate comparison.

3. No material samples were cut from the structure to measure their structural properties. MIL-HBK-5[5] was the sole source of material properties. It is assumed that they met the specification, but it is a pass/fail criterion. Should the yield point exceed the specification by 15% (for example), it is accepted but would have an impact on the FEA.

4. Tolerance stacking: The drawings and IGES (universal electronic solid model) files were used to construct the ANSYS model. In actuality, tolerances do exist and the

[5]Military Handbook 5, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH, July 2000.

combination of such tolerances may affect the load sharing and pre-stress conditions of the structure.

5. Strain gauge accuracy: The strain gauges used have a guaranteed accuracy of within 3%.

2.3 Analysis by Picatinny Arsenal

The purpose of the Picatinny model was to provide results quickly with a simpler CAS model, with the ARL model providing more detailed results at a later date. Therefore, most of the structurally insignificant features were removed from the Picatinny CAS model and half symmetry was assumed.

The model was built from step files generated via ProENGINEER (ProE)[6]. The ProE files were provided by Raytheon Missile Systems, Inc., the contractor for CAS. All the threaded faces were tied together—the equivalent of gluing or welding the faces together. Contact was defined on all the other mating interfaces simulating the interaction between touching bodies. Since this model assumed half symmetry, an additional symmetry boundary condition (figure 9) was applied.

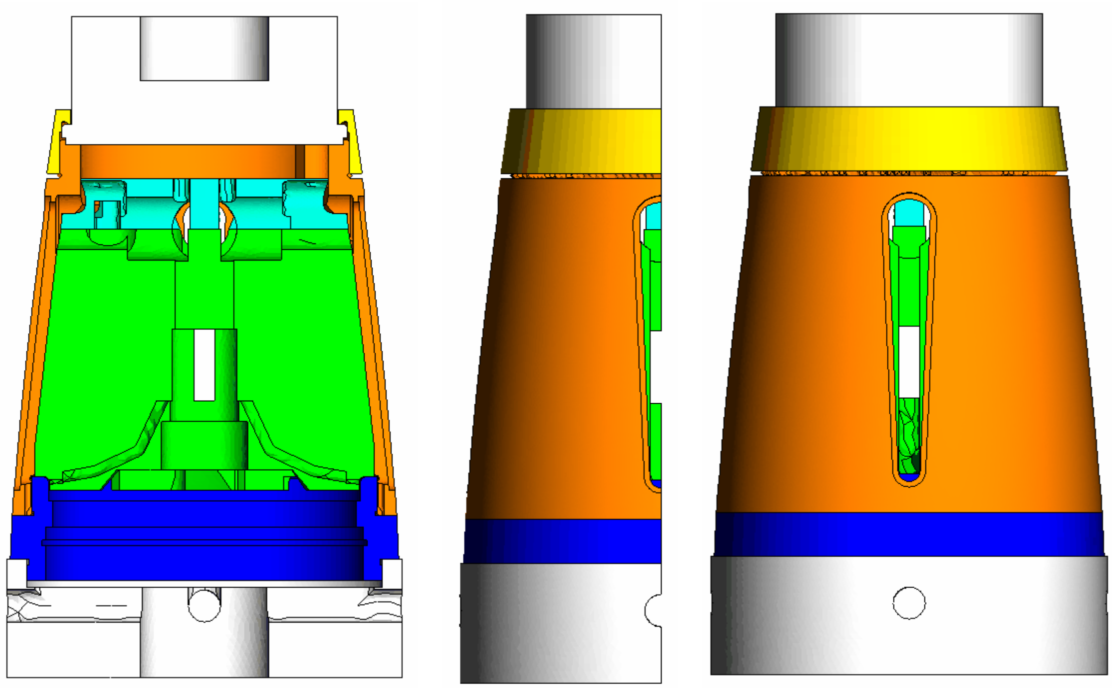

Figure 9. ABAQUS half-symmetry model employed by Picatinny.

Pre-loads were applied to the model, as shown in the exploded diagram (figure 10). Two bolts, the top clamp and the two internal plates were preloaded to match the load applied during assembly of the CAS.

[6]ProENGINEER is a registered trademark of Parametric Technology Corporation.

To improve the accuracy of the strain readings, the areas of interest were coated with low modulus membrane elements. This places the integration points of the membrane elements on the surface of the part eliminating the extrapolation error with nodal values.

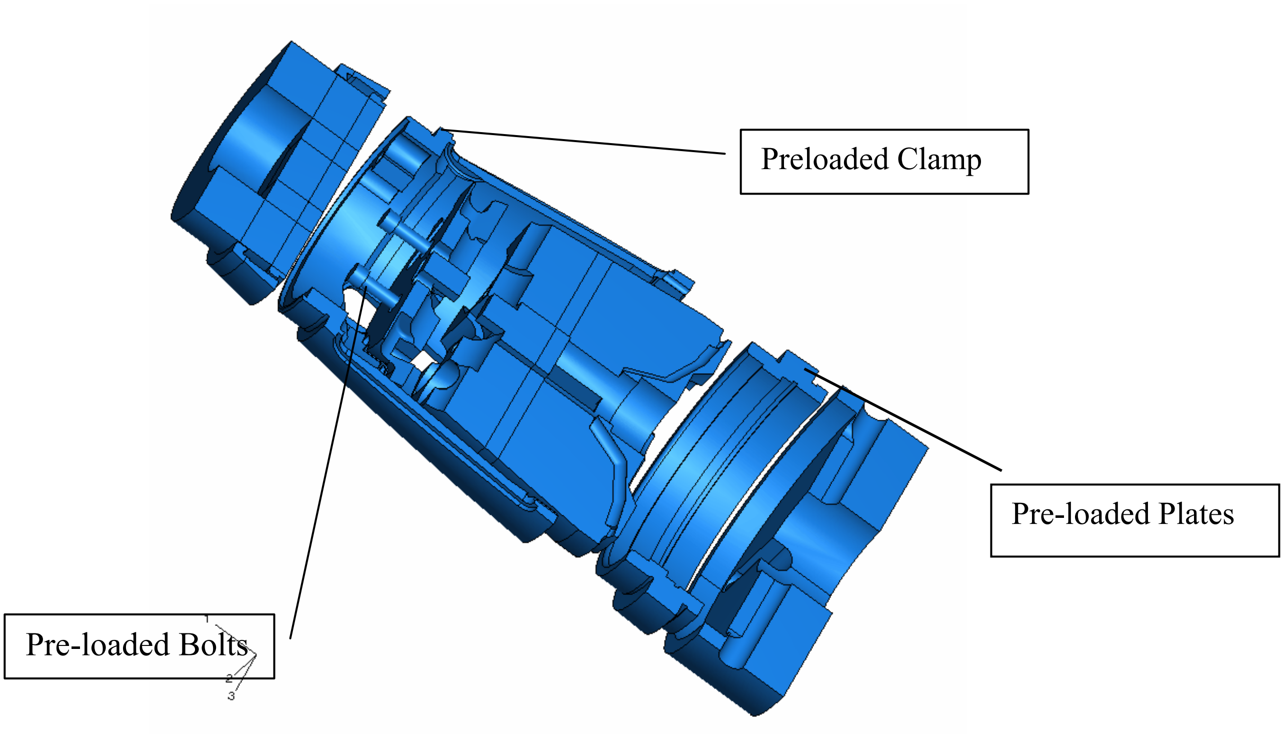

Figure 10. Boundary conditions for the half-symmetry ABAQUS model.

2.4 Finite Element Results for Picatinny Analysis

The reaction force and displacement of the case were measured. The displacements are portrayed graphically in figure 11. The reaction force was 65,775 pounds force (lbf); this matches well with the applied load of 65,806 lbf. The maximum displacement was 0.02575 inch. This is significantly less than the 0.039 inch from the crush test. This may be attributable to part defeaturing and removal of a gap between the outer shell and load ring stiffening the structure.

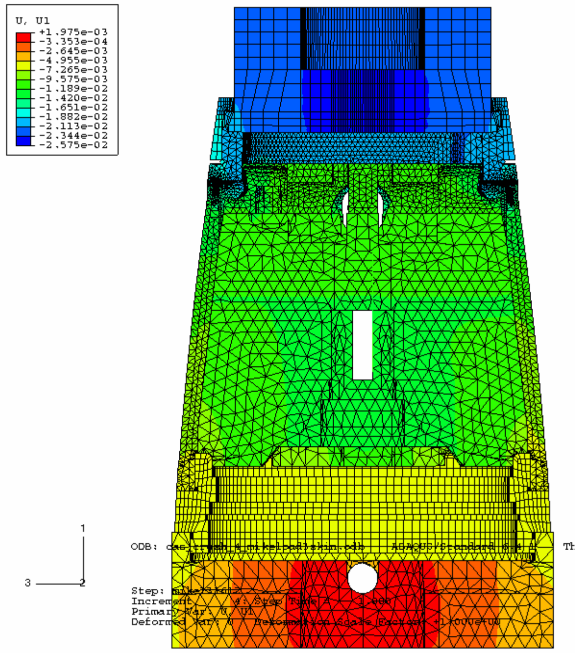

Figure 11. ABAQUS finite element model.

Table 2. Comparison of Picatinny predictions to actual strain gauge readings, PMP + 5% (µ strains)

(actual gauge reading/ABAQUS estimate, error percent below. Because of the half-symmetry of this model, not all gauges were analyzed - "NA")				
gauge_1	**gauge_2**	**gauge_3**	**gauge_4**	**gauge_5**
NA	673/612	NA	NA	NA
	9.1%			
gauge_6	**gauge_7**	**gauge_8**	**gauge_9**	**gauge_10**
432/423	NA	-192/-25	629/620	-1690/-1537
2.1%		**87.0% (note 1)**	**1.4%**	**9.5%**
gauge_11	**gauge_12**	**gauge_13**	**gauge_14**	**gauge_15**
-2070/-1937	590/722	-1700/-1722	-197/-488	NA
6.4%	**-22.4% (note 2)**	**-1.3**	**-147.7% (note 1)**	
gauge_16	**gauge_17**	**gauge_18**	**gauge_19**	**gauge_20**
-1470/-783	-1740/-1493	496/463	-208/-1835	299/445
46.7% (note 1)	**14.2%**	**6.7%**	**11.8%**	**-48.8 (note 2)**
gauge_21	**gauge_22**	**gauge_23**	**gauge_24**	**gauge_25**
NA	-54/30	NA	NA	NA
	43.9% (note 2)			
gauge_26	**gauge_27**	**gauge_28**	**gauge_29**	**gauge_30**
NA	NA	NA	-1580/-1420	-2360/2472
			10.1% (note 3)	**-13%**
gauge_31	**gauge_32**	**gauge_33**	**gauge_34**	**gauge_35**
NA	NA	-2360/-2472	NA	NA
		-4.7%		
gauge_58	**gauge_59**	**load lbs**	**disp in**	
NA	NA	-131,512	-0.0400	

1. Error may be attributable to tied constraints, course mesh.
2. High gradient; refined mesh would reduce error.
3. High gradient, location of gauge unclear

3. Conclusions

The Picatinny model being half-symmetry will provide approximately half the number of locations for which to compare strain results with the ARL model. The investigators from each activity have provided these analyses for the purpose of aiding the decision-making process and to reinforce each other's assessment of structural integrity of the Excalibur CAS. When half symmetry exists, it is expedient to choose this analytical option to reduce computation time and conserve computing and human resources. However, for state-of-the-art guided artillery projectiles, this is true for a limited number of parts of the round. It would be recommended to employ this technique as much as possible and to use the full-featured model when necessary.

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